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Developing 3-D mine-scale geomechanical models in complex geological environments, as applied to the Kiirunavaara Mine

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ABSTRACT

An understanding of the relationship between the geological environment and rock mass behaviour induced by mining activities can lead to hazard reduction through knowledge-based design. However, characterisation of complex and heterogeneous rock masses that typify mining environments is difficult. A methodology to characterise these types of rock masses, based largely on classical statistics, geostatistics and an extension of previous quantitative structural domaining work, is presented and applied to the Kiirunavaara Mine, Sweden. In addition to a new perspective on intact rock strengths of geological units at the mine, a correlation was found between modelled volumes of clay, modelled RQD, newly identified structural domains and falls of ground. These relationships enabled development of a conceptual model of the role of geology in rock mass behaviour at the mine. The results demonstrate that the proposed methodology can be useful in characterisation of complex rock masses.

1. Introduction

Mining induced rock mass behaviour is a result of the interaction between the mining and geological environments. An understanding of the role of 3-D geomechanical characteristics in rock mass behaviour can lead to significant opportunities for risk-mitigating engineering design. Typically, geomechanical models of mining environments are developed by using classification methods such as Geological Strength Index (GSI) or Rock Mass Rating (RMR). These methods were originally developed and calibrated for civil engineering excavations, such as tunnels, and are well suited to homogeneously jointed rock masses. Alone, however, they are unsuited to heterogeneous rock masses in which the strength and stiffness is affected by characteristics in addition to discontinuities, which typify the geological environment of many mines. Adaptations of GSI for heterogeneous rock masses have been developed (Hoek and Karzulovic, 2001; Marinos and Hoek, 2001); however, they are still mostly based upon planes of weakness, and as identified by Mandrone (2006), are less applicable when weakness exists in other forms, such as alteration. Over the life of a mine, geomechanically relevant data is often collected for different purposes, and there can be difficulty synthesizing these multiple sources of data into a coherent geomechanical model. Also, data availability and coverage issues specific to mining caused by economical and physical constraints (such as shotcreting limiting available mapping faces) often compound the difficulties associated with this process.

This paper proposes a methodology to create a 3-D mine-scale geomechanical model for complex and heterogeneous rock masses using readily available data from mines, such as geologically logged core, Rock Quality Designation (RQD) and mapped discontinuities. Luossavaara-Kiirunavaara Aktiebolag's (LKAB) Kiirunavaara Mine, in northern Sweden, is used to illustrate the techniques. This geomechanical model created for the mine is then compared to fall of ground information, with the intention of developing a conceptual model of causes of rock mass behaviour and identifying indicators of problem areas. In 2008, the Kiirunavaara Mine became seismically active (refer to Dahnér et al. (2012) for a detailed description). Several studies were undertaken by LKAB to understand the underlying causes and nature of the behaviour (Sjöberg et al., 2011, 2012; Vatcher et al., 2014). Recent underground mapping, core logging and laboratory testing campaigns done in support of these projects have revealed that the rock mass is heterogeneous, with variable characteristics across both the 5 km length and >1000 m depth of the orebody. An additional potential complication for geomechanical characterisation of the rock mass is that there are volumes of clay alteration, which are often meters to tens of meters in their longest dimension.

Previous studies at the Kiirunavaara Mine have been limited in scope with respect to development of a geomechanical model. The majority of these studies were limited in breadth of analysis, often focusing on portions of the available data at the time of each study (Henry and

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Marcotte, 2001; Lindgren, 2013; Mattsson et al., 2010; Rådberg et al., 1989). Much additional data collection and analysis has been done since these studies with the intention of increasing the geomechanical understanding of the rock mass, providing a good opportunity to enhance knowledge.

The data analysis techniques presented to create large-scale 3-D geomechanical models were intentionally selected for their compatibility with characteristics of the geology and typical limitations associated with data from mining environments, such as sparse coverage and few samples. The methodology utilises standard statistical tests, geostatistics, and an extension of previously published techniques related to quantifiable identification of structural domains.

2. Kiirunavaara Mine

The Kiirunavaara Mine is a large sublevel caving mine that produces approximately 28 million tonnes per annum of iron ore. With the deepest production levels currently at approximately 800 m below surface (Level 1051 m), the rock mass is seismically active and rockburst prone. The newest main haulage level is Level 1365 m (see Fig. 1), and sublevels currently have a 28.5 m separation. Mine coordinates are approximately aligned with the cardinal directions, and the Y coordinates (positive axis aligned with south), which crosscut the orebody, are used to divide the orebody into blocks for production and ore handling (see the numbered ore pass groups along the orebody in Fig. 1).

The magnetite orebody extends approximately 5 km along strike, which is nearly north–south, with a varying width from meters to over 150 m and a dip of 50-70° towards the east (positive X-axis in mine coordinates). For a detailed description of the geology, refer to Geijer (1910). The most specific geological classifications at the mine are done during core logging, whereas underground geological mapping uses more generic geological classifications. The mine distinguishes ore rock types based on their grade and contaminant concentration. Footwall rock types are divided into three major classifications; granite, skarn or trachyte-trachyandesite (referred to as syenite porphyries at the mine). The trachyte-trachyandesite is further divided into 5 subgroups based on their mineralogy, texture and/or alteration, referred to as Sp1 through Sp5. Porphyry dykes are also common in the footwall region. Hangingwall material, mainly rhyodacite (referred to as quartz-bearing porphyries at the mine), is similarly divided into 5 subcategories (Qp1 through Qp5) based on their mineralogy, texture and/or alteration. Underground geological mapping identifies the ore units based on grade and contamination (the same units as mapped during core logging), however footwall and hangingwall materials are mapped in less detail underground than they are during core logging. Fewer hangingwall data are available by either mapping or core logging due to underground access and ore-targeted drilling.

Some of the rock mass at the Kiirunavaara Mine has undergone significant alteration. This alteration is in the form of both replacement of minerals by clay as well as leaching, leaving the rock porous (Berglund and Andersson, 2013). The clay-altered lens-shaped volumes are visible underground and in core from diamond drilling (as clay and possibly as core losses), and their extent ranges from centimeters to tens of meters throughout the mine.

3. Data and methodology

The selection of data was based on potential importance to geomechanical characterisation, availability, and reliability. Data analyzed in the development of the geomechanical model of the mine was selected because of their possible relations to intact rock strength, zones of strength and stiffness contrasts, rock mass quality and structural domains. The forms of these data sources available at the Kiirunavaara Mine are described below. Some of this data is routinely collected at the mine, and some was collected during specifically targeted campaigns in support of this and other projects at the mine.

- The diamond drill core database consists of approximately 590 000 m of mostly 28 mm diameter core, from approximately 3000 boreholes (LKAB, 2014a). The extent of the data is shown by Volume A in Fig. 2. With few exceptions, all drilling is from underground, with fans of four holes on average at 50 m spacing along strike targeting orebody definition. The majority of drilling is done from the footwall due to access restrictions. On surface, geologists log these drill holes, identifying geological units, core losses and zones of poor material (such as clay), and RQD.
- A total of 56 unconfined compressive strength (UCS) tests were completed on 11 of the rock units, which are sourced from previous testing done by LKAB employees (such as Andersson and Israelsson,

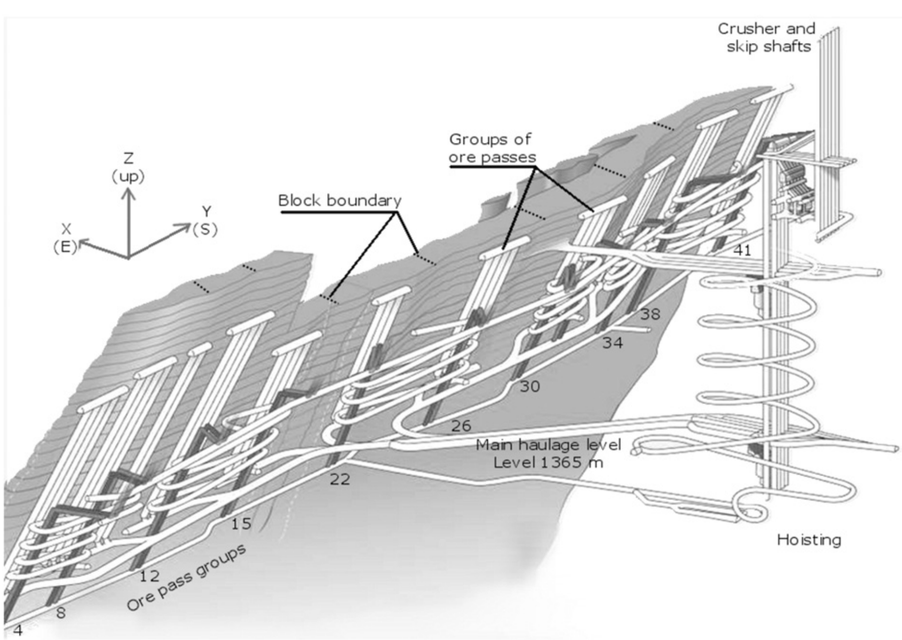

Fig. 1. Sketch of the orebody and mine layout. Production blocks and associated ore pass groups are numbered based on their Y coordinate (numbered at the draw points in this image). Modified image from LKAB.

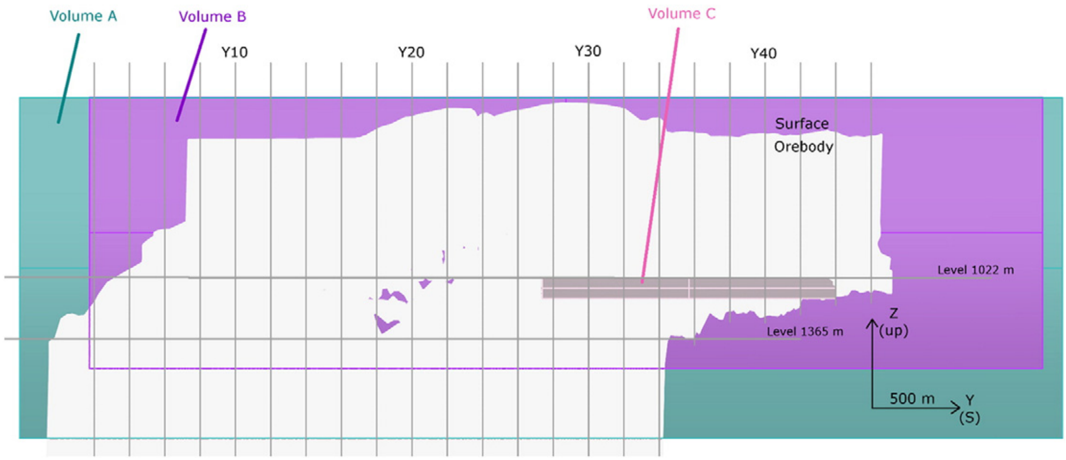

Fig. 2. Data extents (not coverage) represented by boxes overlaid on an outline of the orebody (longitudinal view from the footwall towards the hangingwall). All volumes extend into the hangingwall and footwall. Mine coordinates along orebody strike (Y coordinates) are labeled. Volume A represents the data extents of the drill cores. Volume B shows the data extents of the discontinuities mapped underground. Volume C illustrates the location of extensive underground mapping campaigns to better identify geological features, such as structures and clay altered volumes.

2009), unpublished work (Westblom, 2014) and as a part of this study. Competent and representative samples were selected. Samples were extracted from many locations in the mine, mostly contained by Volume B in Fig. 2.

- Approximately 740 Point Load Strength tests were completed on 20 of the rock units on 28 mm core as a part of this study. The majority of these samples were from Volume C in Fig. 2. Weaker samples were preferentially eliminated due to sampling technique. An additional 141 Point Load Strength tests were completed by Lindgren (2013) on lump samples from varied locations throughout the mine. These 141 tests were not used in this study to reduce the introduction of potential sources of error caused by 1) the different sample type, and 2) the different source location.
- Geological data exists from routine underground drift mapping, which focuses on definition of the orebody and the location of different types of ore rock units. The majority of mapping data is in the footwall and in the orebody. Extensive shotcreting limits mapping anywhere except working faces. In addition, a recent underground mapping campaign over the span of one year has provided a more detailed definition of clay zones in Volume C in Fig. 2.
- Over 4000 discontinuities exist in the database from underground drift mapping (LKAB, 2014b). The extents of these data are represented by Volume B in Fig. 2. All mapped joints have information about their orientation.
- Geological Strength Index (GSI) has been mapped during underground campaigns (LKAB, 2014c). Data is available between Level 1051 m and Level 1543 m within Volume B (Fig. 2), but data coverage is limited due to shotcreting.
- A recent campaign acquired and analyzed data from underground mapping to provide an understanding of the kinematic regime of the rock mass (Berglund and Andersson, 2013). This is the first major underground campaign specifically related to faults at the mine, and was mostly conducted in Volume C (Fig. 2).
- Rock falls occurring during production are individually documented in reports and stored in a database at the mine. All rock falls have been systematically recorded since circa 2010, with selected events recorded in 2008 and 2009.
- The Kiirunavaara Mine has an extensive seismic network with related information stored in the database. Dahnér et al. (2012) provides a description of the network and mining-induced seismicity.

In complicated rock masses such as at the Kiirunavaara Mine, the importance of using statistics as a basis for analysis is heightened. With such large complexity and quantity of available data, there is a likelihood that geomechanical patterns become too convoluted to analyze without the assistance of statistics. As such, the methodology to build the geomechanical models is based on statistical analysis of physical data, using operational experience and separate data sources for verification where possible.

Geostatistical techniques have been used with success to assess rock masses from a geomechanical perspective for a variety of purposes (Ayalew et al., 2002; Coli et al., 2012; Ozturk and Simdi, 2014; Stavropoulou et al., 2007). These techniques are well suited to data-rich environments that have large-scale changes in characteristics. Due to its robust and quantifiable nature and suitability with complex and heterogeneous geological environments, geostatistics was selected as one of the main spatial analysis techniques to develop the geomechanical model at the Kiirunavaara Mine.

The proposed methodology employs the use of standard geostatistical techniques with additional statistical analysis to understand the large-scale 3-D patterns of rock mass characteristics, such as structural domains, zones of high or low stiffness material and rock mass quality. These areas are first analyzed separately and then subsequently synthesised in 3-D space to create one geomechanical model. Geostatistical analysis is limited to identification of volumetric characteristics of the rock mass, and specifically excludes identification of discrete features such as faults, for which targeted underground mapping is better suited.

As with all modelling, control data for calibration and verification purposes is essential. Good candidates include data related to rock mass behaviour as well as seismicity, rock falls and drift mapping. Data sets which are too sparse for statistical analysis or which are in an unsuitable format (such as maps or photos) can be used as control data.

4. Geomechanical characterisation

4.1. Intact rock strength

A complete understanding of the intact strength differences between geological units does not yet exist at the Kiirunavaara Mine. In the literature, petrographic data has been used to evaluate intact compressive rock strength through regression, expert systems, and artificial intelligence (Alvarez Grima and Babuška, 1999; Gokceoglu, 2002; Gokceoglu et al., 2009; Singh et al., 2001), however, insufficient data was available for this study to use such an approach. As an alternative, UCS and Point Load Strength tests were selected to evaluate intact strength. Typically, the results from Point Load Strength tests are used to gain additional strength information by scaling the Point Load Strength

Indices ($Is_{(50)}$) to UCS values. Numerous empirical relationships exist in literature for the scaling of $Is_{(50)}$ data to UCS values (Bieniawski, 1975; D'Andrea et al., 1965; ISRM, 1985; Kahraman, 2001; Kaya and Karaman, 2015; Kohno and Maeda, 2012). Most of these relationships use linear scaling as suggested by ISRM (1985):

$$UCS = kIs_{(50)} \tag{1}$$

where k is the scaling factor. The scaling factor suggested in the testing standards ranges from 20–25, however it is acknowledged in the standards and confirmed by others (previously listed) that this value may vary between 15 and 50 and is highly dependent upon rock type (ISRM, 1985). Some authors, such as Kaya and Karaman (2015), have found even lower scaling factors.

Since this scaling is dependent upon rock type, it is critical to first approach grouping of rock units by intact rock strength using statistical tests. The purpose of this analysis is to identify 1) the underlying distribution of strength parameters, 2) groups of geological units that share common strengths, and 3) the estimated mean strengths and standard deviations of these groups. There is insufficient data availability at the mine to determine if intact rock strength is dependent upon location, not only geological units.

Due to the large number of samples, the Kolmogorov-Smirnov test was used on the $Is_{(50)}$ data to evaluate all possible groupings of geological units. This method uses the cumulative distribution functions of two samples to evaluate if differences exist between the location and shape of the distribution functions, and was selected due to its robust, non-parametric nature. Each sample was represented by one $Is_{(50)}$ value; an average value for the sample was used if there was more than one acceptable data point. $Is_{(50)}$ data were then scaled to UCS data for each group of geological units individually to estimate the strength of each group according to the following equation:

$$k = \left(\frac{\mu_{UCS}}{\mu_{Is_{(50)}}}\right) \tag{2}$$

where k is the scaling factor, μ_{UCS} is the average UCS from the UCS tests and $\mu_{Is_{(50)}}$ is the average $Is_{(50)}$.

Based on the results from the Kolmogorov-Smirnov tests and considerations of sample size, it is evident that some mapped geological units likely share common underlying distributions. The most likely grouping of geological units into strength groups based on the statistical analysis are shown in Fig. 3, where the distribution of the grouped and scaled $Is_{(50)}$ data is shown by box plots, providing information about the distributions of each group through the visualisation of their quartiles. No significant difference between the distributions of 1) the 5 types of hangingwall units or 2) the remaining ore types were found, however not all units were well represented. Units that have limited sample numbers are starred (*). Additional point load tests would improve the precision and accuracy of this analysis. Based on Kolmogrov-Smirnov tests and χ^2 tests, all data before and after grouping by multiple geological units indicated normal distributions, with the exception of the ore material with few samples (ore, higher contaminant levels). This may be a result of few samples or at least two unique distributions of strength within these geological units.

The UCS data for each group of geological units are overlaid on the scaled $Is_{(50)}$ data in Fig. 3 as stars. Additional UCS tests would significantly improve the accuracy of the estimated strengths, in particular for groups with few UCS samples. Both the UCS data and the Point Load Test data had a relatively wide spread, in particular in the majority of the footwall material. The porphyritic dyke and Sp2/Sp4 groups showed higher strengths than the other groups. Kolmogorov-Smirnov tests on the scaled point load test data and the UCS data sets indicated that the distributions between the two data sets (Point Load Test data and UCS test data) for individual grouped geological units were consistent.

There is a significant spread of estimated intact rock strengths for the geological units present at the Kiirunavaara Mine. Lindgren (2013) showed that increasing the pervasive alteration into softer minerals, such as chlorite, carbonates and clay, lowers the intact rock strength through analysis of Point Load Strength tests conducted on lump samples; however, the current study does not have sufficient data to evaluate the role of alteration on intact strength at the mine. Although very clear during core logging and underground site investigations, the intact rock strength tests do not illustrate the significant strength and stiffness difference of some of the weaker units found at the mine, such as clay, due to preferential sampling.

4.2. Volumes with clay alteration

Due to the significantly different material properties of clay compared to the surrounding rock, and due to the total volume of clay

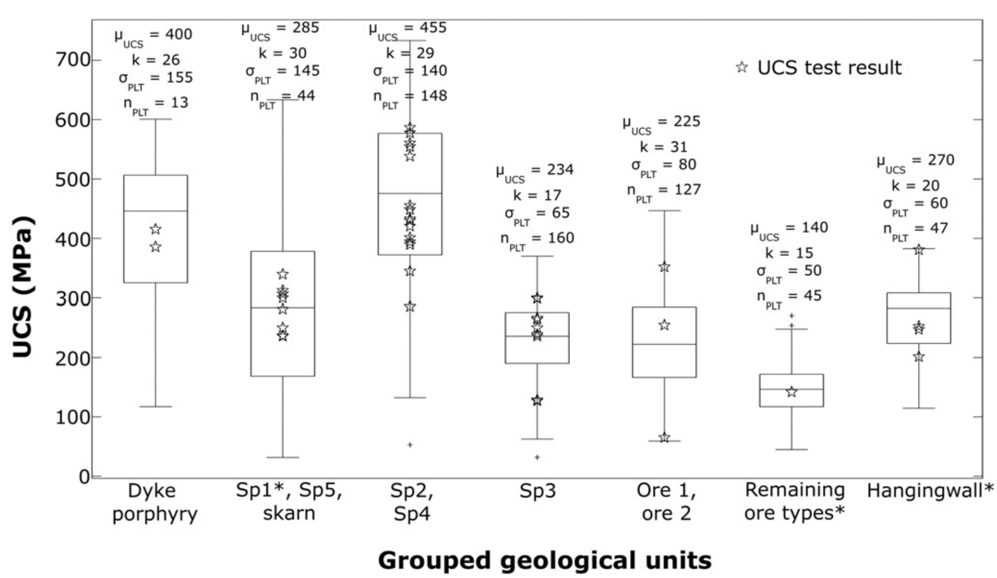

Fig. 3. Scaled Point Load Strength test results (box plots) and UCS test results (stars) by grouped geological units. Boxplots of the point load tests for each grouped geological unit show outliers (considered as +/− 2.7 * standard deviation) as crosses. Average UCS from the UCS tests (μ_{UCS}), the scaling factor (k), the scaled standard deviation from the Point Load Strength tests (σ_{PLT}), and the number of Point Load Strength tests (n_{PLT}) for each group are presented over the box plots.

present, the locations of volumes of clay alteration are an important consideration for the geomechanical model at the Kiirunavaara Mine. 3-D volumes of clay based on isotropic search parameters from mapped data were developed by Mattsson et al. (2010). However, this work has not been updated to reflect newly acquired data and knowledge.

Geostatistical techniques were applied to understand the underlying spatial distribution of these clay volumes. This includes an analysis of appropriate search parameters via semi-variograms and then interpolation of the data. The interpolated model from the drill core data was compared to drift mapping to evaluate accuracy of the technique for this rock mass.

A common difficulty in identifying clay material in drill cores is that clay is often washed away by the drilling water and does not remain as part of the core. To account for this, both mapped clay and core loss in the core logging data (LKAB, 2014a) were considered to be indications of clay altered zones.

Indicator semi-variograms were created to determine 1) if directional anisotropy exists, and 2) the appropriate search parameters for the composited clay data from core mapping. Sample compositing was used to reduce bias caused by variable sample length. The clay and core loss data were downhole composited on 0.5 m intervals, as the majority of sample lengths were shorter than this value. The semivariograms indicated that the major and minor search ellipse axes are horizontal (Fig. 4). The major axis is semi-perpendicular to orebody formation. The semi-major axis was steeply dipped towards the north. The major and semi-major axes had approximately the same range, however the range was significantly reduced in the minor axes direction. As evident in Fig. 4, the minor axis, approximately aligned along orebody strike, has a significantly smaller range than the borehole spacing (circa 50 m). This indicates that the data from the drilling has insufficient density for the use of geostatistical techniques to estimate clay volumes at the Kiirunavaara Mine. This could be related the possible genesis method of the hydrothermal clay alteration at the mine; hydrothermal fluid travels through existing discontinuities until it reaches a volume of the rock mass which is susceptible to larger amounts of alteration. The preferential travel along existing discontinuities can result in locations of clay that have a discrete nature, rather than a volumetric one. Due to this discrete nature, this data a difficult candidate to consider for interpolation methods.

However, a simple spatial analysis of the density of clay indicators from the core data in 3-D space using search radii identified from the semi-variograms yielded a model of the clay volumes (not clay alteration found in joints) that could be calibrated to clay mapped underground where data was available, see Fig. 5a) and b). Fig. 5c) shows the calibrated clay model with the underground mapping data. Calibration was done visually to determine which isosurface value in the clay model corresponded to the mapped data. Within the calibration volume, this isosurface represents the density at which the clay indicators represent a volume of the rock mass that has more clay. The only mapped clay volumes that were not represented in the model were volumes which had no associated drill core data. The calibrated model does not necessarily represent volumes that have entirely been altered to clay, rather volumes that have a higher concentration of clay than their neighbours. At the Kiirunavaara Mine, this simplistic form of spatial analysis of core data has the potential to assist with prediction of location and size of clay volumes prior to drifting. Tighter exploration drill spacing and additional underground mapping in other areas of the mine have the potential to improve future models.

4.3. Rock mass quality

When considering the data available over the entire mine, neither GSI (LKAB, 2014c) nor RMR data sets are good candidates for geostatistical analysis. The RMR data set at the mine is very sparse in both number of sample points as well as their physical locations. GSI has more data points than RMR, but still suffers from poor coverage. However, the RQD data set (LKAB, 2014a) is much more complete, and is amenable to geostatistical analysis.

Two previous works exist using geostatistics to estimate RQD at the Kiirunavaara Mine. The first was limited to a section of the rock mass located in the north (Henry and Marcotte, 2001), and the second used isotropic search parameters to develop a mine-scale model (Cotesta, 2011). To update the model with newly mapped data and to provide additional analysis, a new mine-scale model that used anisotropic search parameters was created.

Using similar techniques as previously discussed, anisotropy was found to exist through the analysis of semi-variograms. Despite results from Henry and Marcotte (2001) illustrating that the range of the semi-variograms indicated insufficient drill spacing for geostatistical analysis of the analyzed portion of the rock mass (only the northern portion), the semi-variograms of the current database for the entire mine indicated otherwise. Based on the ranges from the semi-variograms search radii were evaluated to be 100 m along strike, 100 m across strike, and 80 m vertically, which are greater than the maximum drill spacing of 50 m.

Models of RQD were created using inverse distance, as a preliminary evaluation technique. Kriging methods have the potential to improve these models. An example vertical slice through the mine-scale RQD model is illustrated in Fig. 6 in combination with a longitudinal projection of the orebody. Distinct zones of lower RQD crosscut the orebody, in particular in the southern end (Fig. 6). These zones are physically associated with the calibrated clay volume model; low RQD is found both inside and in the immediate vicinity of the volumes that are estimated to

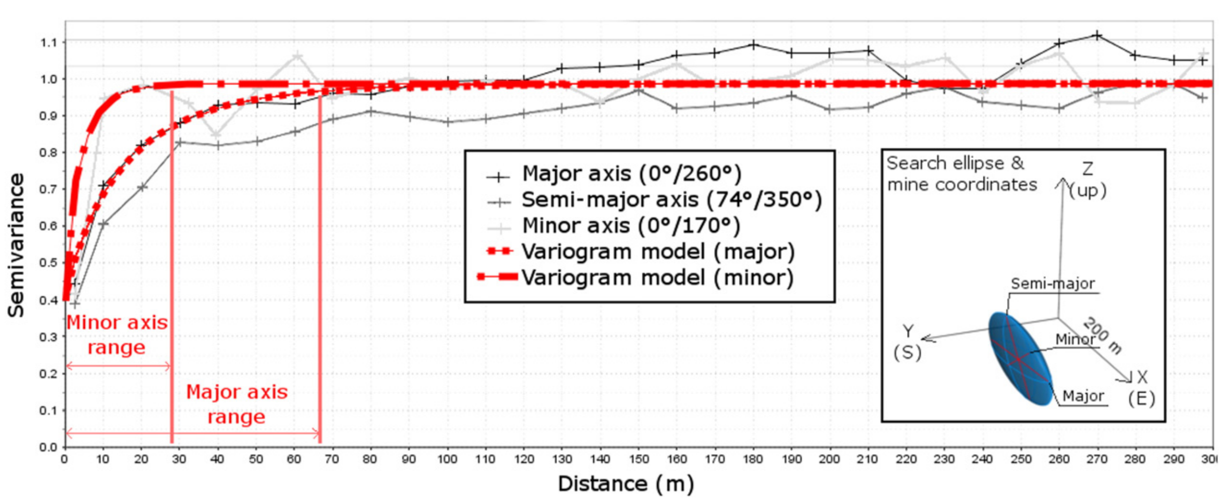

Fig. 4. Semi-variograms in the major, semi-major and minor search ellipse directions. Search ellipsoid is visualised with mine coordinates.

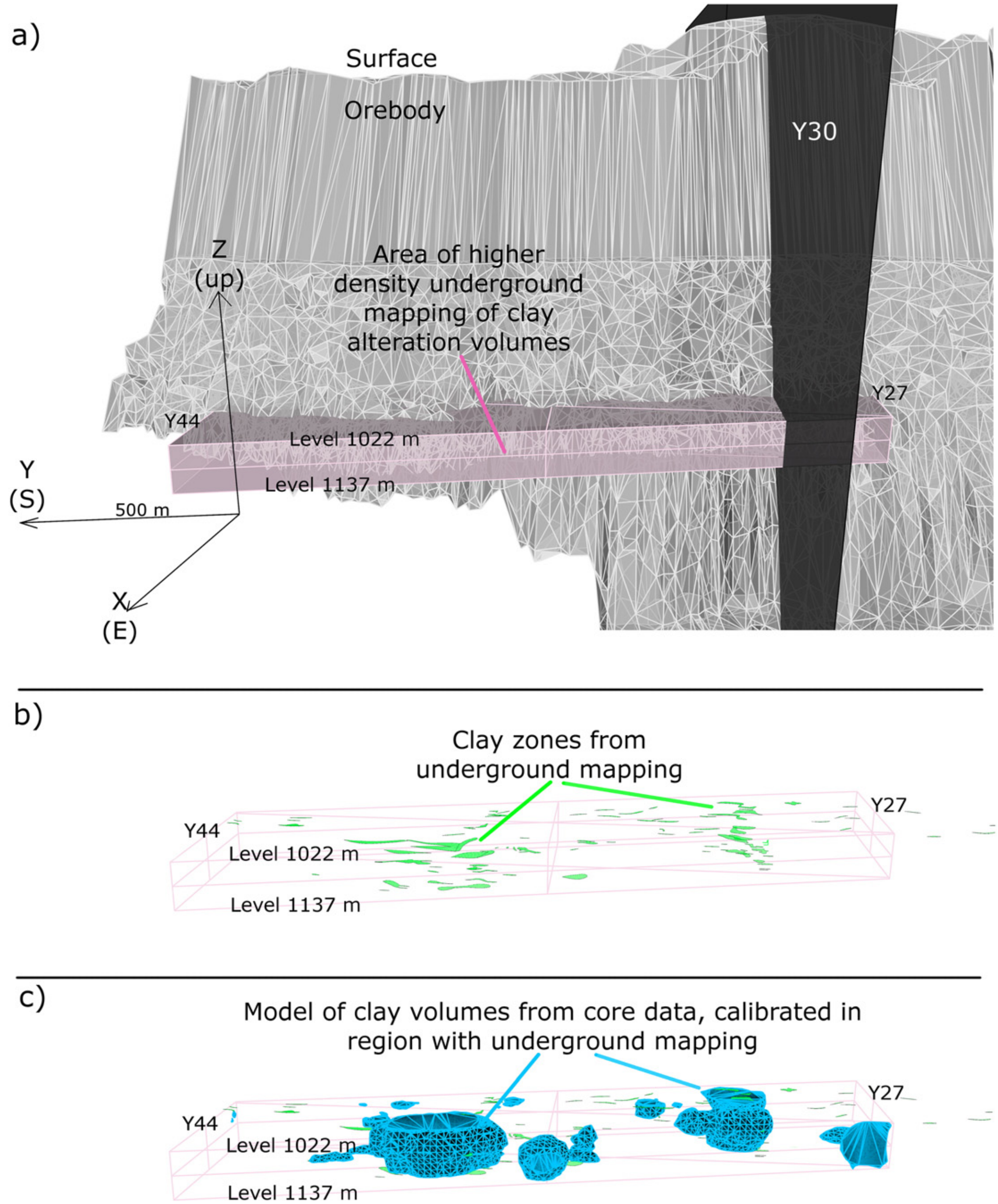

Fig. 5. Calibration of model of clay volumes from core data with underground mapping data (view from the hangingwall towards the footwall). Area of higher density underground mapping shown in a), mapped clay volumes are presented in b) with the overlaid clay model from the core data in c).

have more clay alteration (Fig. 6). Consistent with the mine-scale results found by Cotesta (2011), RQD increases with depth in the northern portion of the rock mass, with a sharp contrast at approximately the Level 950 m.

4.4. Structural domains

The last structural domaining done at the mine scale was completed in 1995 (Holmstedt, 1994, 1995), however the structural domains found by Rådberg et al. (1989) are more commonly used. Since that time, some additional work on identifying domains has been done sporadically for specific volumes of the mine. The current study updates the structural domain model by incorporating historical and newly acquired data (LKAB, 2014b).

Due to the importance of the identification of structural domains, multiple techniques have been developed to assess their boundaries (Escuder Viruete et al., 2001; Jimenez-Rodriguez and Sitar, 2006; Martin and Tannant, 2004; Piteau and Russell, 1971; Zhou and Maerz, 2002). Most techniques have limitations, however, such as their reliance upon a priori geological knowledge, lack of evaluation in 3-D space, appropriate distance metrics for clustering, etc., which may misrepresent the underlying spatial distribution of joint sets.

Available discontinuity data at the mine scale in the Kiirunavaara Mine is limited to drift mapping of joint orientations at active faces (shotcrete limits mapping of completed excavation). The nature of this data eliminates the possibility of multivariate clustering as suggested by Zhou and Maerz (2002), as only dip and dip direction is readily available at the mine scale.

Piteau and Russell (1971) developed an effective and simple technique to identify the locations of structural domains. Their technique is based upon the mathematical definition of structural domains; within each domain, the slope of the cumulative sum of dip or dip direction is

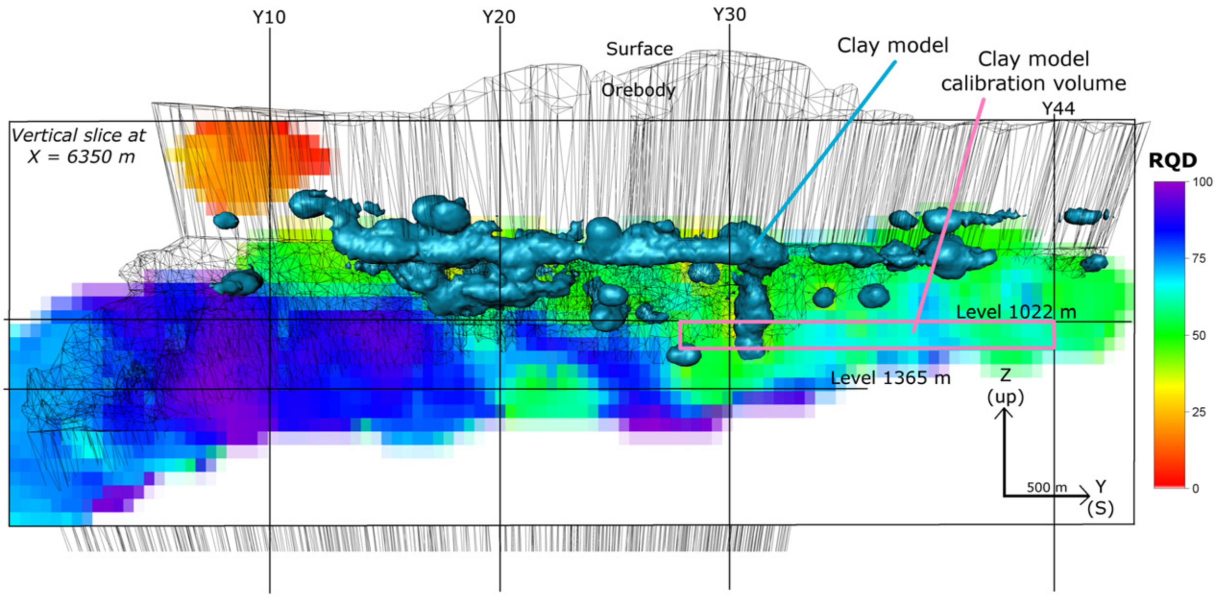

Fig. 6. Example vertical slice through the mine-scale RQD model through X = 6350 m viewed from the footwall overlaid on a longitudinal projection of the orebody. The RQD model is represented by the block model, where values are scaled by colour. The mine-scale clay model (from Section 4.2) is superimposed on the RQD model, in addition to its calibration volume.

constant. The major limitation of their domain location technique is that it is based upon evaluating data along a 1-D ray or in a 2-D plane. Identifying the correct locations of domains using this technique assumes that the domains can be defined upon the user selected ray or plane, and that there are no other domains in other directions. The success of this approach is highly dependent upon the underlying spatial distribution of the joint sets.

An extension of Piteau and Russell (1971) has been developed to quantitatively identify domains in 3-D. Identified domains are then statistically evaluated using similar strategies as presented by Mahtab and Yegulalp (1984) and Martin and Tannant (2004). The proposed technique for quantitative identification of structural domains is detailed below.

1. Create a block model representing the span and extent of the original, cleaned data. Block dimensions are user specified; the intended scale of the domains, measurement spacing and geological environment are evaluated to determine this.
2. Within each block, for every joint measured, calculate the slope of the cumulative sum of 1) strike and 2) dip. Filtering of blocks based on user-defined minimum number of data points and linear fit parameters is recommended.
3. Using the slope of the cumulative sum and/or dip direction, apply geostatistical interpolation methods to supplement gaps in the data. The decision of which data to use should be based upon statistical analysis of the underlying data. With most data sets, the slope of the cumulative sum of dip is the most appropriate source to use, as when strike is used, there is a numerical discrepancy between 0° and 359° that does not represent a large physical direction difference. The methodology could be adapted for other mapped joint characteristics, such as joint roughness, however due to data availability at the mine this was not explored.
4. Using isosurfaces (3-D analog of an isoline or contour) of the block model, identify continuous volumes in 3-D space representing volumes of distinct structural domains. The selection of isosurfaces requires user input. Particular attention should be paid to large changes in shape/location of isosurfaces. Distinct and individual isosurfaces represent domains; however, the numeric values of the isosurfaces are irrelevant.
5. Statistically and visually compare the stereonets for the determined structural domains.

This technique was tested using the underground discontinuity mapping data at the Kiirunavaara Mine to evaluate the location and shape of the structural domains. Domains were identified using cubic blocks of 30 m edge length, that had greater than five data points and an r^2 value from linear regression greater than 0.95. A significant number of the structures measured at the mine had strikes that were orientated around 0° N, so the cumulative sum of dip was the most appropriate metric. Isotropic inverse distance was applied to the block model to interpolate the data. Alternative methods of interpolation have the potential to improve this model.

Example slices through the interpolated block model are shown in Fig. 7 in conjunction with a wireframe of the orebody, where each block is coloured based on its value of the slope of cumulative sum of dip. Changes in colour represent distinct 3-D volumes that share similar slopes of cumulative sum of dip, indicating distinct domains.

The 3-D isosurfaces from the domain block model were used to group and test the original data points. Mahtab and Yegulalp (1984) suggested a method of statistically comparing stereonets based on pole count in equal area windows, and then using the χ^2 test to test if the distribution of the pole count for two stereonets is different, where a difference represents a new domain. Due to sample size limitations associated with the χ^2 test, Martin and Tannant (2004) adopted the window technique, however used the Pearson product–moment correlation coefficient (Pearson's r) as an indication of similarity between two stereonets. For the Kiirunavaara Mine, Pearson's r, Spearman's rank correlation coefficient (Spearman's rho (ρ)) as well as the Kendall rank correlation coefficient (Kendall's tau (τ) coefficient) were tested to evaluate statistical similarity between stereonets. For the joint sets in the Kiirunavaara Mine, the use of Spearman's ρ correlation coefficient and Kendall's τ were found to be most appropriate since the joint set data series after the count of poles in the windows are discrete and non-normal.

The results from the domaining analysis at the Kiirunavaara Mine highlight that the domains have 3-D shapes at the mine-scale, which cannot always be accurately represented in 2-D. The methodology is useful not only to identify domains and their shape, but also to explore rotations of joint sets within one domain. The magnitude of a joint set's rotation and intended use of the structural domains form the basis of the decision about if it constitutes a domain boundary. Statistical comparison of the stereonets can assist with this process via quantification of how different two stereonets are. At the Kiirunavaara Mine, one of

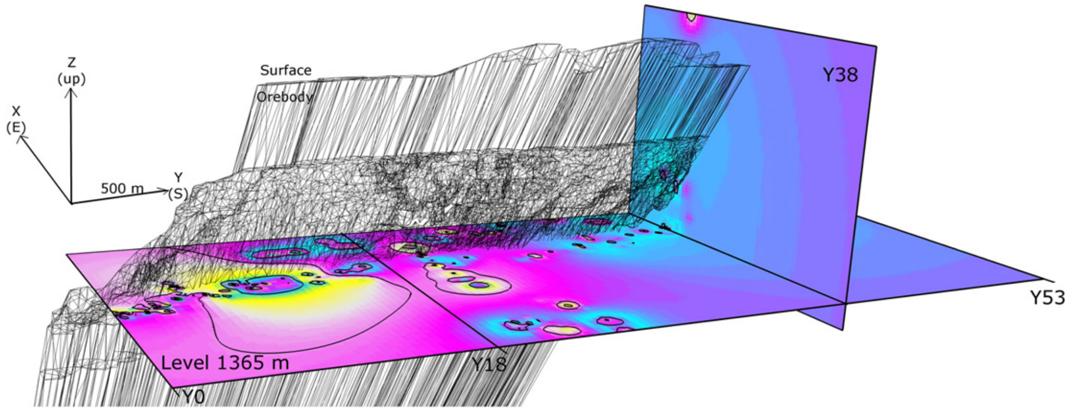

Fig. 7. Example slices through the slope of the cumulative sum of dip block model (30 m cubes) used to identify structural domains (seen from the footwall towards the hangingwall). The colour of each block represents the slope of the cumulative sum of dip for all joint sets mapped inside of that block. The values themselves are inconsequential; it is the location of changes in the values that represents possible structural domain boundaries.

the identified domains consists of a joint set that rotates within the volume. The three volumes presented in Fig. 8 are statistically from the same domain (see domain stereonet in the upper left corner of Fig. 8) using both Spearman's ρ correlation coefficient and Kendall's τ. However, as shown by the other stereonets in Fig. 8, the orientation of the main joint set varies slightly between the individual volumes.

At the Kiirunavaara Mine, transitions between domains at the mine-scale were rarely sharp. One example to the contrary, however, corresponds with a known, mapped geological feature. Despite not being used as a priori boundary during the analysis, where the rock mass transitions from north to south into a more clay altered volume (from approximately Y 28 and southwards), there is a sharp domain change. In this southern portion of the orebody, only two domains have been identified at the mine-scale (Fig. 9). They consist of many joints, and joint set identification is difficult (Fig. 9). The joint sets have a more random component in the heavily clay altered volumes of the rock mass.

The 3-D domains identified for the rock mass using the suggested technique offered a significant improvement when compared to vertical extension of domains previously analyzed as suggested by Rådberg et al. (1989). More unique domains were identified, in different locations, with clearer definition of joint sets and transition zones between domains. Statistical comparison of the old and new domains showed that the new domains were more distinct than the domains identified by Rådberg et al. (1989).

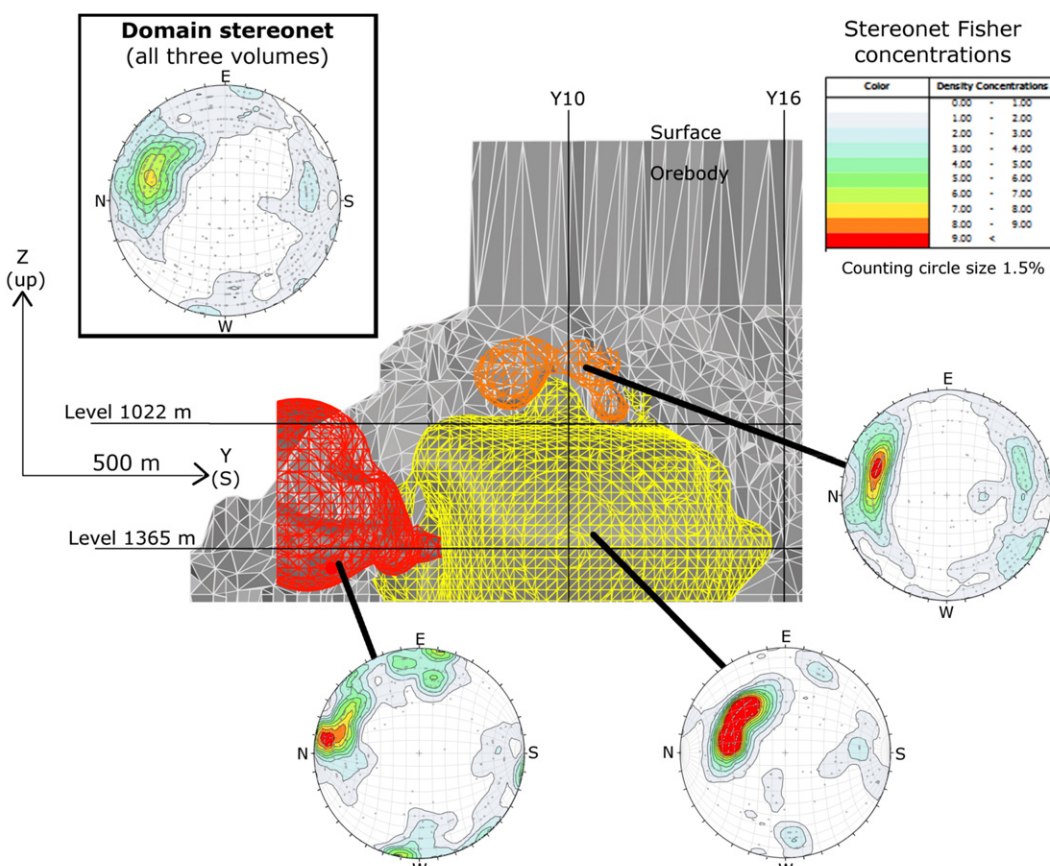

Fig. 8. Example of one domain (domain stereonet in upper left) at the Kiirunavaara Mine with slight variation of orientation of the major joint set for different volumes within the domain. Fisher concentrations for the poles are shown on equal area lower hemisphere stereonets. Stereonets are rotated so they are aligned with the mine coordinate system.

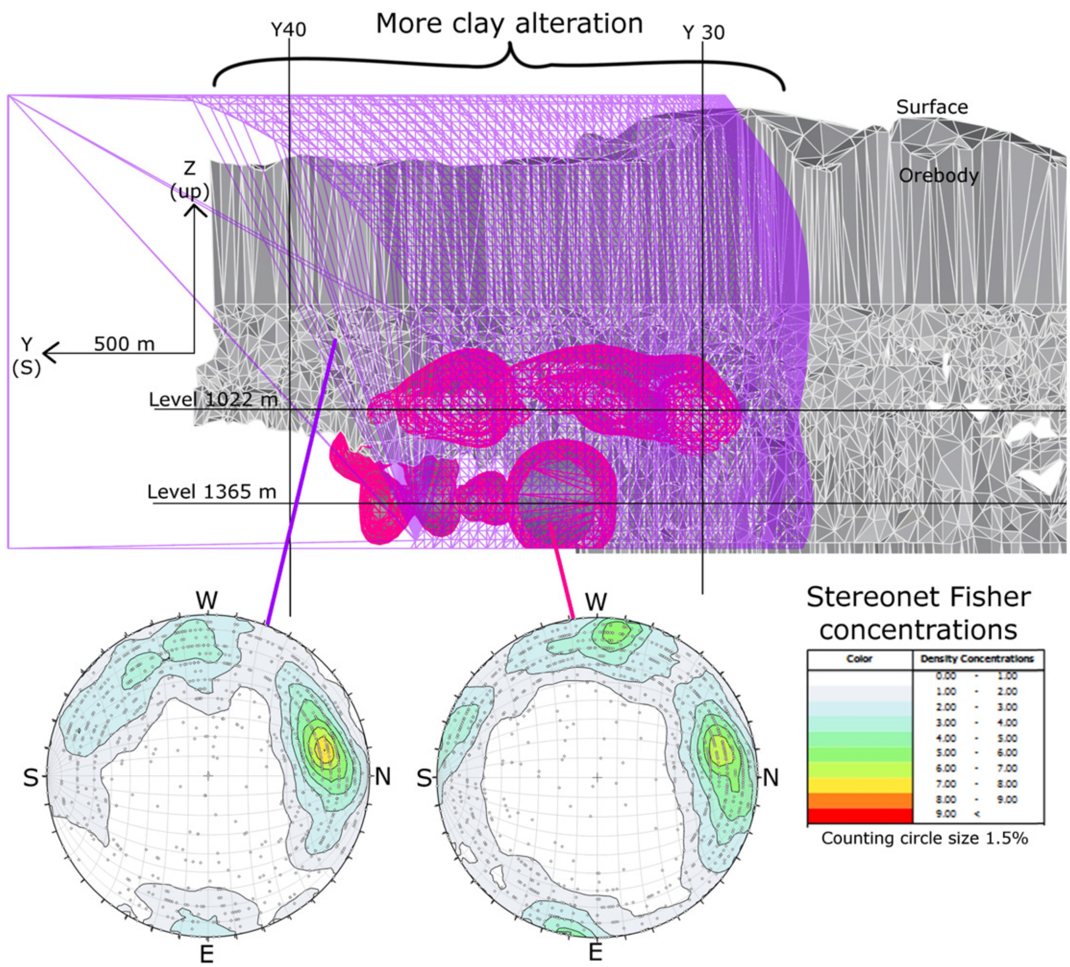

Fig. 9. Domains in the southern portion of the rock mass overlaid on the orebody as seen from the hangingwall. Domains are represented by the shaded wireframes, and their associated lower hemisphere equal area stereonets are provided. Stereonets are rotated so they are aligned with the mine coordinate system.

4.5. Faults

Numerous faults (discontinuities with identifiable shear displacement) are present at the mine. Berglund and Andersson's (2013) underground mapping work around Y 34 on the Level 1051 m, Level 1060 m, and Level 1079 m identified many faults. The majority of these faults are steeply dipping and follow the strike of the orebody (Berglund and Andersson, 2013). Currently, their length, spacing and persistence is unknown. Evidence of faults can also be seen during core logging in the form of slickenslides along discontinuity surfaces. Visible underground, many of these ore parallel structures, which exhibit slickenslides, are hematite coated with a mirror like surface and undulate on the scale of meters. Few orebody perpendicular faults have been mapped underground. Seismic clustering of events by the mine has identified possible fault structures, however only one structure has been confirmed by underground mapping, which was subsequently used in numerical stress analysis by Sjöberg et al. (2011). The currently available data does not enable a mine-scale characterisation to include faults, since mapped data is mainly limited to that done by Berglund and Andersson (2013).

5. Correlation to falls of ground

Based on the geomechanical characterisation, the portion of the rock mass which contains significant volumes of clay has different characteristics than the unaltered portion. The different characteristics are not limited to the clay volumes; rather the entire rock mass surrounding the clay. This is apparent from information related to jointing. Surrounding the clay volumes there are lower RQD values, few distinguishable structural domains, and a more random component to the discontinuities. Because of the seemingly controlling nature the clay zones have over the geomechanical characteristics of the rock mass, it is logical to evaluate if there is a correlation between the calibrated clay model and falls of ground.

The falls of ground at the Kiirunavaara Mine are often associated with seismic events, in the form of shakedown and/or bursting. With available data, it is difficult to accurately distinguish between these causes of the falls of ground, so all of these events were considered in this analysis. All fall of ground events at the mine are comparable since the support system is the same for almost the entire extent of the rock fall database. The direction of the major principal in situ (pre-mining) stress at the Kiirunavaara Mine is horizontal and approximately perpendicular to the strike of the orebody, whilst the intermediate and minor principal in situ stresses are nearly equal (Sandström, 2003). When viewing the data from the approximate direction of principal in situ stress, a correlation between the modelled clay zones and the falls of ground is evident (Fig. 10). The majority of the falls of ground are concentrated in the rock mass surrounding the clay zones.

There were significantly fewer falls of ground from approximately Y 23 and northwards. This could be related to the lack of clay volumes in the area, although additional calibration of the clay model in that volume is required.

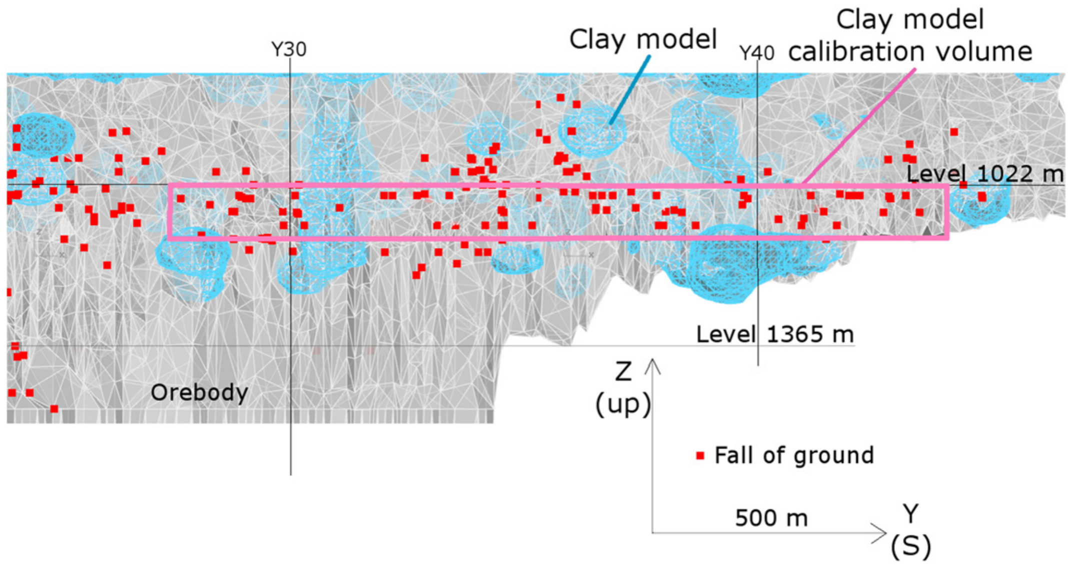

Fig. 10. Falls of ground (squares) versus the calibrated clay volume model (shown from the footwall towards the hangingwall). Viewed from the direction of major principal in situ stress (pre-mining).

6. Discussion

Analysis of intact rock strength at the Kiirunavaara mine showed large variations not only between the groupings of geological units, but within them. This spread has implications for the geomechanical model and future rock engineering analyses. Representing the rock mass with constant strengths and stiffnesses is a simplification that cannot fully capture the rock mass response related to intact strength variation. The causes of this variation are unclear; the role of alteration in intact rock strength needs to be further evaluated. Additional UCS values (from UCS tests or triaxial tests) for geological groups with few of these data points may improve the scaling of the Point Load Strength tests. At this stage, how to scale the intact rock strength to rock mass strength for this complex geological environment remains unresolved.

At the Kiirunavaara Mine, a link exists between modelled clay volumes and falls of ground. Considering how the in situ stresses in this region likely behave, a possible explanation of this mine-scale behaviour is suggested. Since the volumes with clay alteration have a lower stiffness than the surrounding rock mass, the stresses will flow around the clay zones and concentrate in the more competent rock. This increase in stress magnitude in the surrounding rock mass has the potential to initiate new failure not necessarily induced by mining, such as those possibly indicated by the RQD model and the random component of the joint sets in the region. Stress concentrations caused by the clay volumes combined with mining induced stress changes have the potential to explain some of the behaviour. Numerical stress analysis in combination with more detailed study of the failure modes of the ground falls will be carried out in a future stage of this investigation to further explore this hypothesis and its implications on rock mass behaviour at the mine.

The methodology presented, as applied to the Kiirunavaara Mine, resulted in an increased understanding of the geomechanical characteristics of the rock mass. It successfully improved upon many aspects of geomechanical characterisation, such as the identification of new structural domains and a new understanding of the distributions of intact rock strengths. The methodology worked particularly well with the large quantity of borehole data combined with separate data sets for calibration. As an additional benefit, the development of a geomechanical model using these techniques and comparison of that model to rock mass behaviour highlighted where supplementary data collection could add the most value.

The methodology is robust; it has the potential to be adapted to different types of data in other mining environments. However, a priori knowledge of the rock mass was used to select the analysis techniques. Due to the smoothing nature of geostatistics, consideration must be given to if the parameters of interest are good candidates for interpolation. Data sets for interpolation must show spatial correlation over a greater distance than the data spacing, which is evaluated through semi-variograms. The highest resolution of the interpolation is a function of the input data set; interpolation requires supporting data points and accuracy of the results cannot be improved without well-positioned data. Provided the data supports interpolation, the presented methodology is well suited to geological environments with heterogeneity and alteration, and/or environments that have domain boundaries with irregular shapes in 3-D.

7. Conclusion

Through enhancement of the understanding of the geomechanical characterisation of the Kiirunavaara Mine, a conceptual model of some aspects of the rock mass behaviour was developed. Clay volumes (represented by a model based on borehole data calibrated to underground mapping) correlated to the geomechanical characteristics and behaviour of the rock mass. The rock mass in the immediate vicinity of the volumes of clay alteration had lower RQD values, more random jointing, and a higher concentration of falls of ground than the surrounding rock mass.

Consideration of multiple sources of data in 3-D space through the application of geostatistics was a key component to the development of this new conceptual model. The methodology presented, based on statistics, geostatistics and an extension of previous quantitative domaining work, is of interest to other mines that have complex and heterogeneous geological environments, specifically those which have volumes of alteration, structural domains which possibly have complex shapes in 3-D, or other characteristics which are well suited to interpolation methods. The methodology is well suited to geological environments that are appropriate data for interpolation; data types which can logically be interpolated between data points and that are spatially correlated over a greater distance than the data spacing. The use of geostatistics on multiple data sets that are often available at mines (such as borehole data, structural mapping data, etc.) has the potential to give indications of problem areas, provided the interpolation is well calibrated against data that is distinct from the input data.

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